Unraveling Aerosol-Atmosphere Relationships in the Arabian Gulf Through Artificial Intelligence

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Abstract

This study analyzes the correlation between Aerosol Optical Depth (AOD) and various atmospheric and oceanographic parameters over Abu Dhabi and the Arabian Gulf (Latitude: 24.4416° N; Longitude: 54.6166° E). High-precision monitoring stations provided data on mean temperature, salinity, and chlorophyll concentration in the Arabian Gulf. This dataset spans a four-year period from January 2018 to August 2022. Additionally, AOD data across multiple wavelengths and precipitable water measurements (in cm) were sourced from NASA AERONET stations, while complementary atmospheric and oceanographic data were obtained from the UAE Ministry of Climate Change and Environment. The study utilized MATLAB-based tools to analyze weather conditions and establish correlations. The results indicate that AOD is closely linked to chlorophyll concentration, mean salinity, and precipitable water. While mean temperature and salinity align well with AOD trends, specific months—September, October, and November—exhibit increased AOD levels, with other atmospheric parameters demonstrating a linear relationship with these trends.

Keywords: Aerosol Optical Depth (AOD), Arabian Gulf Atmosphere, AERONET Observations, Aerosol–Ocean Interaction, AI Analysis

Introduction

Recognizing the critical necessity of understanding atmospheric dynamics and their impact on both local and global climates, the UAE government has launched several initiatives to study Aerosol Optical Depth (AOD) and climate change. Agencies such as the UAE Space Agency, the Environment Agency – Abu Dhabi, and the Ministry of Climate Change and Environment have developed sophisticated monitoring systems to track aerosol concentrations and their relationship with air quality and climate patterns. The UAE's dedication to climate research is further evidenced by its active participation in global collaborations, including the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. Furthermore, the nation is investing in advanced satellite technology to monitor AOD, utilizing this data to assess regional pollution levels and formulate emission reduction strategies. The UAE is also committed to fostering a sustainable, low-carbon economy through frameworks like the UAE National Climate Change Plan 2017-2050 and the Clean Energy Strategy, aiming for 50% of the country's energy to be renewable by 2050.

Additionally, collaborations with international institutions focus on mitigation strategies such as renewable energy, carbon capture, and sustainable urban planning, enhancing the UAE's climate resilience and contribution to global solutions.

Aerosol Optical Depth (AOD) is a vital atmospheric parameter quantifying the presence of aerosol particles—such as dust, smoke, or pollutants—that influence Earth's climate and air quality. AOD measures the extent to which these particles obstruct sunlight transmission through the atmosphere; higher values indicate greater aerosol concentration and reduced visibility. Investigating AOD in the Arabian Gulf, in conjunction with various atmospheric parameters, offers significant insights into the region's air quality and environmental shifts. This region is particularly compelling due to its unique convergence of desert dust, urbanization, maritime influences, and emissions from the oil industry.

In the Arabian Gulf, AOD is modulated by a complex interplay of variables, including temperature, humidity, wind speed and direction, precipitation, salinity, precipitable water, chlorophyll concentration, and cloud cover. The region's high temperatures, especially in summer, drive intense dust storms that significantly elevate AOD levels. The arid climate results in low relative humidity, allowing dust particles to remain small and easily dispersed. prevailing winds, particularly from the northwest, transport substantial dust volumes, while wind direction determines whether aerosols originate from desert dust or urban pollution. Although infrequent, precipitation can reduce AOD via wet deposition. Cloud cover plays a multifaceted role, as aerosols act as condensation nuclei, potentially altering local weather patterns. Furthermore, high AOD reduces solar radiation reaching the surface, impacting the region's energy balance. This study conducts a detailed investigation into AOD, mean sea surface temperature, mean seawater salinity, precipitable water, and chlorophyll concentration.

Study Area: Arabian Gulf & Strait of Hormuz

Atmospheric data for this study was collected from the Arabian Gulf, a body of water in the Middle East situated between the Arabian Peninsula to the south and Iran to the north. It connects to the Gulf of Oman and the Arabian Sea via the strategic Strait of Hormuz.

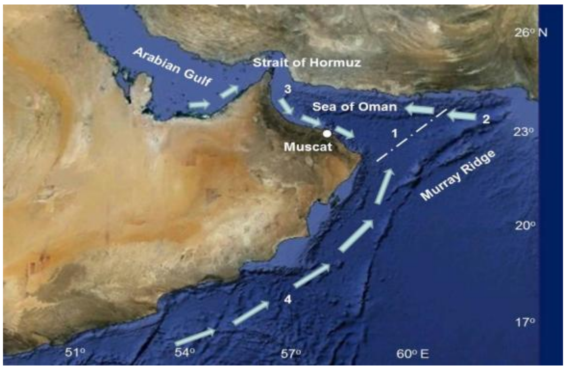

Figure 1: Study Area Map

Aeronet Station

The Masdar AERONET (Aerosol Robotic Network) station, located in Masdar City, Abu Dhabi, UAE, plays a pivotal role in providing real-time data on regional aerosol properties, including AOD. Masdar City is renowned for its sustainability and renewable energy initiatives, and its AERONET station contributes essential data for atmospheric research, specifically regarding dust and pollution in the Arabian Peninsula.

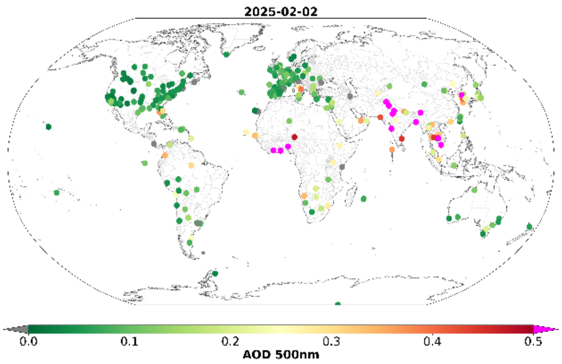

Figure 2: Masdar City AERONET Station

AOD data utilized in this study were retrieved from the NASA AERONET station located in Masdar City, Abu Dhabi, at the precise coordinates of Latitude 24.4416° N and Longitude 54.6166° E.

Figure 3: Satellite View of Station Location

Data Collection & Preprocessing

For this research, AOD data at different wavelengths (AOD_380nm, AOD_1640nm) and Precipitable Water (cm) were retrieved from the Masdar AERONET station for the period from January 2018 to August 2022. Monthly mean datasets were sourced from the NASA website. Concurrently, environmental and oceanographic parameters were obtained from the UAE Ministry of Climate Change and Environment's seawater quality dataset (2015-2023). This study utilizes monthly averages for seawater temperature, salinity, and chlorophyll concentration.

Data preprocessing involved rigorous error correction and evaluation of combined datasets. The success of correlation studies relies on accurate parameter selection and error mitigation. Preprocessing steps included the elimination of irrelevant parameters, imputation of missing data, and correction of erroneous values. Data integrity was verified using Principal Component Analysis (PCA) to identify principal components and eliminate irrelevant dependencies.

Month	AOD_164(	AOD_380r	Precipitab	AnnualMean Temp Arabian Gulf DegreeC	Annual mean Temp Sea of oman Degree C	AnnualMean salinity Arabian Gulf mg/L	Annual mean Saliity Sea of oman mg/l	AnnualMean Chlorophyll Arabian Gulf Ug/L	AnnualMean Chlorophyll Sea of oman Gulf Ug/L	Data_Qua	Latitude(d	Longitude	Elevation(meters)
2020-MAR	0.257399	0.422946	1.685919	30.3	29	37.5	35.5	1.62	1.53	lev20	24.4416	54.6166	4
2020-APR	0.240674	0.424956	2.080092	30.3	29	37.5	35.5	1.62	1.53	lev20	24.4416	54.6166	4
2020-MAY	0.229386	0.438055	2.399529	30.3	29	37.5	35.5	1.62	1.53	lev20	24.4416	54.6166	4
2020-JUN	0.210395	0.521143	2.426673	30.3	29	37.5	35.5	1.62	1.53	lev20	24.4416	54.6166	4
2020-JUL	0.302458	0.578709	3.3707	30.3	29	37.5	35.5	1.62	1.53	lev20	24.4416	54.6166	4
2020-AUG	0.284456	0.750015	3.869246	30.3	29	37.5	35.5	1.62	1.53	lev20	24.4416	54.6166	4
2020-SEP	0.140661	0.415982	1.771164	30.3	29	37.5	35.5	1.62	1.53	lev20	24.4416	54.6166	4
2020-OCT	0.090984	0.301304	1.590007	30.3	29	37.5	35.5	1.62	1.53	lev20	24.4416	54.6166	4
2020-NOV	0.098223	0.412323	2.198384	30.3	29	37.5	35.5	1.62	1.53	lev20	24.4416	54.6166	4
2020-DEC	0.072264	0.316009	1.822043	30.3	29	37.5	35.5	1.62	1.53	lev20	24.4416	54.6166	4
2021-JAN	0.105603	0.28239	1.301492	29.05	29.01	39.06	37.3	1.4	0.65	lev20	24.4416	54.6166	4
2021-FEB	0.106572	0.342824	1.649255	29.05	29.01	39.06	37.3	1.4	0.65	lev20	24.4416	54.6166	4
2021-MAR	0.302139	0.52528	1.547749	29.05	29.01	39.06	37.3	1.4	0.65	lev20	24.4416	54.6166	4
2021-APR	0.186938	0.363044	1.321695	29.05	29.01	39.06	37.3	1.4	0.65	lev20	24.4416	54.6166	4

Figure 4: Data Processing Workflow

Data Analysis

This section analyzes the monthly averages of measured AOD values across different wavelengths. Figure 5 presents the data plot of the mean monthly parameters at the Masdar AERONET station, while Figure 6 depicts the three patterns of AOD measurements over time. Figure 5 specifically represents Single Scattering Albedo (SSA) values as a function of wavelength (nm) for three measurement conditions at the Masdar Institute, accounting for variations in sky error and size parameters. The three datasets, distinguished by unique colors and symbols, illustrate SSA trends across wavelengths; the blue line indicates higher SSA values compared to the red and brown lines, suggesting variations in aerosol optical properties under different conditions. This highlights the interaction between aerosols and light, particularly scattering efficiency at various wavelengths.

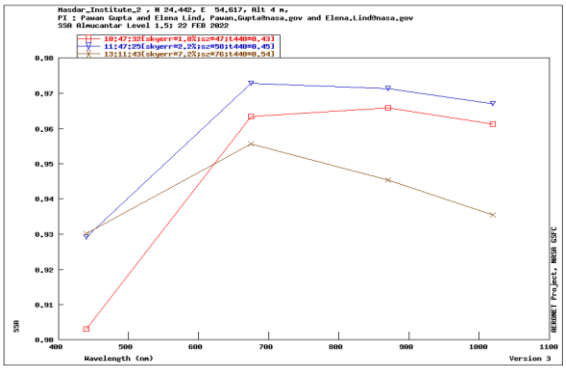

Figure 5: SSA Values vs Wavelength

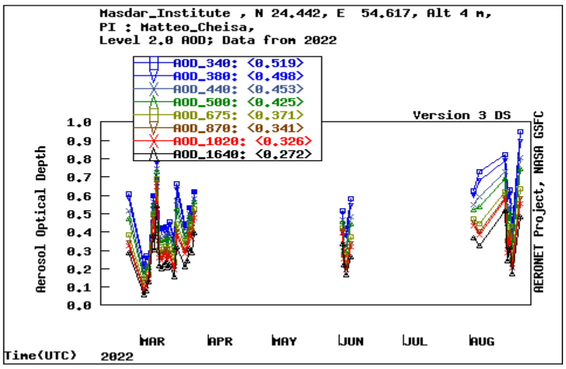

Figure 6: AOD Measurement Patterns

Figure 7 illustrates the trends of four environmental parameters over a specific period: AOD at 380 nm, annual mean temperature, salinity of the Arabian Gulf, and precipitable water. Salinity (yellow line) and temperature (red line) display high, relatively stable values, reflecting the consistent environmental conditions of the Arabian Gulf, with only slight variations or plateaus. Conversely, AOD (blue line) remains near zero, indicating consistently low aerosol concentrations. Precipitable water (magenta line) shows minor fluctuations at lower values. Overall, salinity and temperature dominate in magnitude, emphasizing the steady nature of these parameters relative to the smaller-scale variability of AOD and precipitable water.

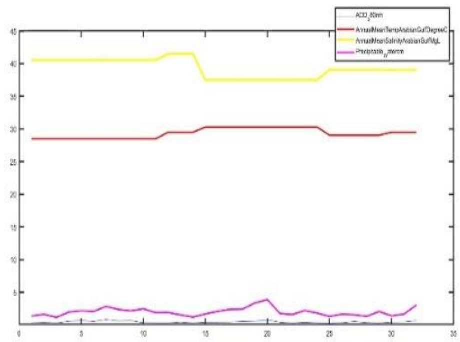

Figure 7: Environmental Parameter Trends

Figure 8 illustrates AOD measurements at wavelengths ranging from 340 nm to 1640 nm over several months in 2022 at the Masdar Institute. Each wavelength is represented by a specific color and symbol. The data reveals higher AOD values in March and August, indicating increased aerosol concentrations, while mid-year months like May and June show relatively lower levels. This suggests seasonal variations influenced by dust storms, pollution, or meteorological conditions.

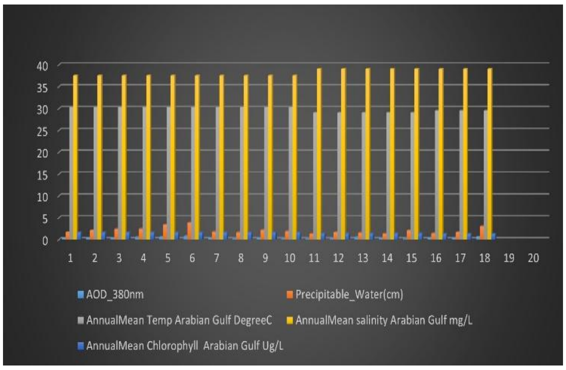

Figure 8: AOD Wavelength Analysis 2022

Further analysis compares several parameters: AOD at 380 nm, precipitable water (cm), annual mean temperature (°C), annual mean salinity (mg/L), and annual mean chlorophyll concentration (µg/L). Both AOD and precipitable water are low, suggesting the region's dry climate limits water vapor availability, indicating a weak relationship between aerosols and atmospheric moisture. High salinity reflects the Gulf's unique marine conditions but does not directly correlate with AOD, although evaporation may contribute to regional aerosols. Chlorophyll levels, indicative of biological activity, are low and show no direct correlation with AOD, though high aerosols can reduce sunlight penetration. Temperature is consistently high but lacks a visible direct correlation with AOD, suggesting aerosol levels are driven more by dust storms and anthropogenic sources than temperature alone.

Results & Discussion

This section evaluates the cross-correlation between AOD and mean temperature, salinity, chlorophyll concentration, and precipitable water. Figure 9 illustrates the scatter plot relationship between AOD at 380 nm and annual mean temperature. The linear regression trend (yellow line, y = -0.443x + 29.54) shows a slight negative slope with a very low R^2 value (0.0074), indicating a negligible inverse correlation. Figure 10 presents the relationship between AOD at 380 nm and annual mean salinity. The regression line (y = -0.01106x + 39.32) and R^2 value (1.254e-06) confirm the lack of a meaningful relationship.

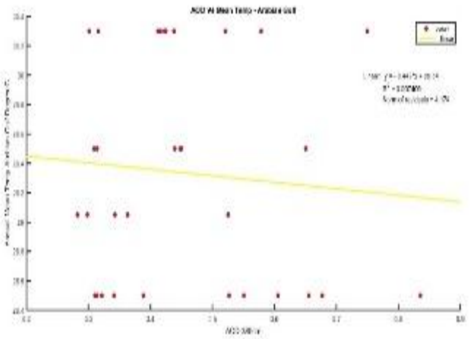

Figure 9: Scatter Plot AOD vs Temperature

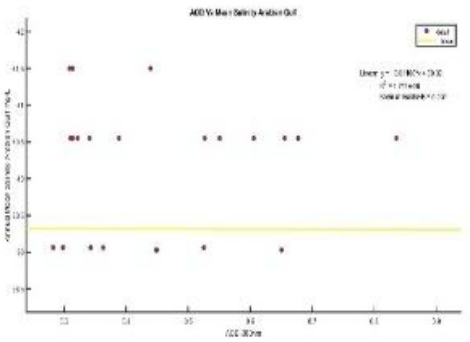

Figure 10: Scatter Plot AOD vs Salinity

Figure 11 illustrates the relationship between AOD at 380 nm and precipitable water (cm). The linear regression (y = 3.035x + 0.6181) and moderate R^2 value (0.4996) suggest a positive correlation, where changes in AOD explain nearly 50% of the variability in precipitable water. Figure 12 demonstrates the relationship between AOD at 380 nm and annual mean chlorophyll concentrations. The regression (y = 0.2094x + 1.424) indicates a slight positive trend, but the low R^2 value (0.04409) implies a weak correlation.

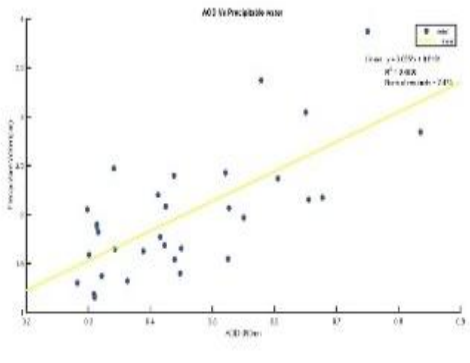

Figure 11: Scatter Plot AOD vs Precipitable Water

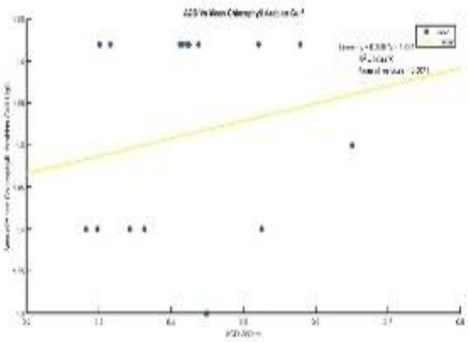

Figure 12: Scatter Plot AOD vs Chlorophyll

Figure 13 further explores the relationship between AOD and chlorophyll concentrations, reiterating the weak correlation observed previously.

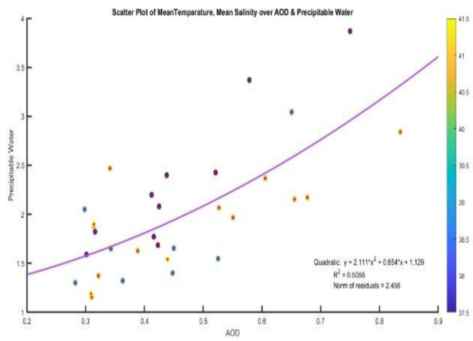

Figure 13: Correlation Analysis

The scatter plot in Figure 14 shows the relationship between AOD and precipitable water, color-coded by temperature. A quadratic regression curve ($y = 2.111x^2 + 0.854x + 1.129$) with an R^2 of 0.5055 indicates a moderate correlation. The plot suggests an upward trend in precipitable water as AOD increases, with higher temperatures clustered at higher values of both variables.

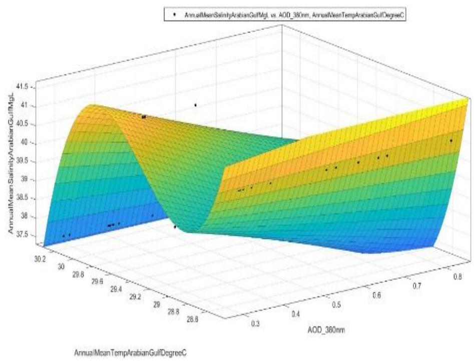

Figure 14: Quadratic Regression of AOD and Precipitable Water

A 3D surface plot analysis visualized the relationship between annual mean salinity, temperature, and AOD at 380 nm. Salinity tends to increase with rising temperatures, though the trend is non-linear. Higher AOD values appear to correspond with increased salinity in certain regions, suggesting a possible link between atmospheric aerosols and salinity fluctuations. The surface plot reveals a curved relationship, implying complex interactions between AOD and temperature influence salinity levels.

In summary, AOD levels exhibit seasonal peaks in September, October, and November. Precipitable water shows the strongest correlation with AOD, while temperature, salinity, and chlorophyll concentration display weaker relationships. Dust storms, pollution, and climatic variations are significant contributors to AOD fluctuations.

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